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Version of attached file:

Published Version

Peer-review status of attached file:

Peer-reviewed

Citation for published item:

Breton, M. and Sbragia, L. (2016) 'Adaptation to climate change : commitment and timing issues.', Working Paper. GERAD.

Further information on publisher's website:

<https://www.gerad.ca/en/papers/G-2016-04>

Publisher's copyright statement:

Additional information:

Les Cahiers du GERAD. G-2016-04

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**Adaptation to climate change:
Commitment and timing issues**

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G-2016-04

January 2016

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Adaptation to climate change: Commitment and timing issues

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January 2016

**Les Cahiers du GERAD
G-2016-04**

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Abstract: We study the impact of timing and commitment on adaptation and mitigation policies in the context of international environmental problems. Adaptation policies present the characteristics of a private good and may require a prior investment, while mitigation policies produce a public good. By developing a stylized model, where some countries coordinate their actions while others do not, we evaluate the impact of strategic commitment and leadership considerations on abatement and adaptation levels, global and individual emissions and environmental costs. Crucially, global and individual environmental costs suffered by countries are found to be greater when adaptation measures can be used strategically.

Key Words: Adaptation, climate change, leadership, mitigation, strategy, timing.

Résumé : Nous étudions l'impact de la séquence des décisions sur les politiques d'adaptation et de réduction des émissions dans le contexte des problèmes environnementaux internationaux. Alors que les politiques d'adaptation présentent les caractéristiques d'un bien privé et peuvent nécessiter un investissement préalable, les politiques de réduction des émissions produisent un bien public. En développant un modèle stylisé, où certains pays coordonnent leurs actions tandis que d'autres ne le font pas, nous évaluons l'impact de l'engagement stratégique et du leadership sur le niveau d'adaptation et de réduction de la pollution, sur les émissions globales et individuelles, et sur les coûts environnementaux. Nous constatons que les coûts environnementaux subis par les pays sont plus élevés lorsque les mesures d'adaptation peuvent être utilisées de manière stratégique.

1 Introduction

One of the consequences of climate change is the increasing frequency of extreme weather events occurring around the globe. Unusually high rainfall is becoming a significant cause of floods, as for example in 2013 in Alberta (Canada) and in Germany, Austria, the Czech Republic and France. On the other hand, droughts are becoming longer, harsher and more frequent, as experienced for instance in 2012 in many U.S. states and in Russia, England and Wales.

To limit climate change, it has been suggested that countries need both to reduce their greenhouse gas (GHG) emissions substantially and sustainably, and to invest in adaptive measures (see the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (2014), the European Commission Climate Action (2015), and President Barack Obama's 2013 Climate Action Plan). Mitigation policies consist in any means to cut down GHG emissions, from reducing deforestation and investing in new clean technologies and renewable energies, to changing consumer behavior; their aim is to prevent the adverse consequences of climate change by reducing its rate and magnitude. Mitigation policies find their roots in the 1992 United Nations Framework Convention on Climate Change and in all the ensuing UN Climate Change Conferences. However, the effectiveness of mitigation policies is limited by two factors. The first one, called *climate inertia*, is intrinsic to the climate system itself. Climate inertia refers to the long period required to reach a new climate system equilibrium after the stabilization of the atmospheric concentration of CO₂ and other greenhouse gases. The second factor is related to the relatively small number of countries committed to GHG emissions reduction, and to the limited extent of their reductions. On the other hand, adaptation policies are designed to alleviate the damages if the adverse consequences of climate change (floods, droughts, heat waves) should materialize. Adaptation policies can take many different forms, such as early warning systems, sea walls, flood levees, irrigation systems, or the development of new crop varieties adapted to drought or changes in temperature.

Although adaptation and mitigation policies are both answers to the risks of climate change, they show some important differences. The first one is the time scale of their impact: while adaptation has the potential to reduce the risks of climate change over the next few decades, mitigation has relatively little influence on climate outcomes over this time scale. The second difference lies in the nature of the investment, where adaptation shows all the characteristics of a private good (with costs and benefits sustained and enjoyed by the individual country that adopts it), while mitigation presents all the features of a public good, including the risk of free-riding.

In line with the IPCC Fifth assessment report statement that “adaptation and mitigation are complementary strategies for reducing and managing the risks of climate change” (IPCC (2014), page 76), in this paper, we study countries' decisions about adaptation and mitigation expenditures, under different assumptions on commitment and timing. In particular, we consider the cases where investments in adaptation measures can be made prior to or simultaneously with mitigation decisions, and the cases where a group of countries can take leadership in environmental measures by making prior commitments.

The literature on adaptation (or self-protection) and mitigation (or abatement) has developed in several directions.¹ A first group of papers analyzes the relationship between adaptation and mitigation policies, that is, whether and when they are substitutes or complements (see, e.g., Ingham et al. (2005), Yohe and Strzepek (2007) and Lecocq and Shalizi (2007)). Other authors focus on how the introduction of adaptive measures against climate change affects the stable size of international environmental agreements (IEA) aimed at reducing GHG emissions (see, e.g., Barrett (2008), Marrouch and Chaudhuri (2011) and Buob and Siegenthaler (2011)). A third stream of the literature studies the optimal mix of mitigation and adaptation policies as responses to the effects of climate change (see, e.g., Kane and Shogren (2000), Tulkens and van Steenberghe (2009), Bréchet et al. (2013) and Farnham and Kennedy (2014)).

Some of these topics have been further developed by explicitly including the timing of decisions in the problem setting. The idea that investments in self-protecting measures against climate change can be made at different moments in time finds its rationale in the IPCC third, fourth and fifth Assessment Reports (IPCC (2001), IPCC (2007) and IPCC (2014)) where *reactive adaptation* (e.g., providing emergency shelters,

¹For a recent survey please refer to Agrawala et al. (2011).

alternative sources of power, sandbags or any other form of help in the event of floods) is distinguished from *proactive adaptation* (e.g., the implementation of early warning systems for floods). This concept of ex-post and ex-ante adaptation is considered in Smith and Lenhart (1996), Fankhauser et al. (1999), Mendelsohn (2000) and Lecoq and Shalizi (2007). It is however important to notice that although the distinction between reactive and anticipative adaptation appears clear, it is difficult to delineate it with precision in a dynamic context such as climate change.

Papers that clearly mention the timing of investments in adaptive measures against climate change include De Bruin et al. (2011), where the level of proactive adaptation is chosen before solving the emissions game in the context of IEA, and Buob and Stephan (2011) and Ebert and Welsch (2012), where adaptation is timed after mitigation in the context of determining the optimal mix between the two environmental policies.

By analyzing the impact of different strategic commitments to adaptation, that is, by focusing on the consequences of the timing of adaptive investments with respect to mitigation decisions, our paper is close in spirit to the one by Zehaie (2009), as we share a similar research question. Indeed, Zehaie (2009) considers three different time sequences of decision, namely, the decision about adaptation is made before, after and simultaneously with mitigation.² In a two-country model, the equilibrium levels of adaptation under full cooperation, noncooperation and semi-cooperation are computed for each case. Two main results are derived: firstly, when adaptation is decided on before mitigation, this generates a strategic effect so that one country passes on some costs of mitigation to the other country. Secondly, the highest level of self-protection is obtained in the semi-cooperative case with precommitted adaptation, followed by the noncooperative case, also with precommitted adaptation, then by the noncooperative case with simultaneous decisions, and finally by the first-best solution.

The aim of our paper is to study the strategic consequences of commitment and timing by considering two types of adaptive investments: the ones that require some prior commitment, and the ones that can be carried out simultaneously with mitigation decisions. In particular, we want to understand the impact of commitment and timing on mitigation and adaptation levels, total emissions, and global and individual environmental costs. In order to do this, we develop a multiple country model where agents minimize their environmental cost by choosing their adaptation and mitigation expenditures, and where a subset of countries of arbitrary size collaborate to reduce pollution emissions. Furthermore, we examine the case where collaborating countries become leaders in environmental policies while non-collaborating countries act as followers.³

The main results of our paper are the following: a greater environmental cost is suffered when countries commit to investments in adaptive measures before they decide about mitigation measures; when adaptation investments are made before the mitigation decisions, countries can take advantage of a strategic effect and increase adaptation to reduce their mitigation effort; and, finally, leadership in responding to the effects of climate change is not beneficial from an aggregate point of view, but it is convenient for the countries that become leaders.

The rest of the paper is organized as follows. Section 2 describes the model; Section 3 computes the equilibrium levels of all variables for the two types of adaptive investments; prior (Section 3.1) and concurrent (Section 3.2) adaptation. Section 4 performs the same analysis for the case where collaborating countries take the leadership in responding to climate change effects. Section 5 outlines the special singular type cases with only collaborating countries (Section 5.1) and only non-collaborating countries (Sections 5.2 and 5.3). Section 6 presents the results and Section 7 draws the main conclusions.

2 The model

We consider n symmetric countries, each of which produces an economic output denoted by o_j . The production activity carried out by a country, in addition to generating economic value, creates emissions according to

²The case of adaptation decisions timed after mitigation decisions is shown to be equivalent to the one where the two environmental policies are decided on simultaneously.

³The idea of leadership is also present in Eisenack and Kähler (2012), where adaptation and mitigation decisions are made simultaneously. They extend the paper by Ebert and Welsch (2012).

the relationship $e_j = \alpha_j o_j$, where α_j is a parameter related to the cleanliness of the production technologies used by country j . We normalize $\alpha_j o_j = 1$ for each j , so that the optimal emissions of each country when there is no environmental concern is equal to 1. Pollution reduces the welfare (e.g., losses in productivity) of each country, and this reduction is increasing and convex in total GHG emissions, denoted by E .

Countries can respond to the effects of climate change caused by pollution with two different environmental policies. The first one is called *adaptation* and it consists in investing in some form of private measures to counteract the consequences of climate change (dams, diversion canals, irrigation, crop diversification). This policy reduces the country's vulnerability to pollution but does not change the pollution level, so that each country's environmental vulnerability is given by

$$v_j = E - b_j$$

where b_j measures the reduction in the level of pollution that has a negative impact on the welfare.

The cost of adaptation for country j is an increasing convex function of b_j , assumed quadratic, that is,

$$\frac{\gamma_A}{2} b_j^2$$

where $\gamma_A > 0$ is the adaptation cost coefficient.

The second environmental policy is called *mitigation* and it consists of any means aimed at curtailing a country's GHG emissions e_j (filters, catalytic converters, expanded forests, etc.). Mitigation is represented by the variable

$$m_j = 1 - e_j$$

where m_j is the reduction in the country's emissions with respect to the base level of 1. The cost of mitigation for country j is an increasing convex function of m_j , assumed quadratic, that is,

$$\frac{\gamma_M}{2} m_j^2$$

where $\gamma_M > 0$ is the mitigation cost coefficient.

Contrary to self-protective adaptation measures, mitigation has the characteristics of a public good, so that the total pollution from all countries is given by

$$E = \sum_{j=1}^n (1 - m_j).$$

The overall environmental cost for a representative country j is thus given by

$$z_j = \frac{\gamma_E}{2} (E - b_j)^2 + \frac{\gamma_M}{2} m_j^2 + \frac{\gamma_A}{2} b_j^2 \quad (1)$$

where $\gamma_E > 0$ is the environmental sensitivity. The objective of a country j is to choose the mitigation and adaptation levels that minimize the environmental cost z_j .

Note that the numeraire can be chosen so that $\gamma_M = 1$ and the total environmental cost is expressed in terms of the mitigation cost coefficient. In this numeraire, the environmental sensitivity is $\omega \equiv \frac{\gamma_E}{\gamma_M} > 0$. We then use the change of variable $a_j = \omega b_j$ for the adaptation investment decision, and the cost function for a representative country j can then be equivalently expressed as

$$c_j = \frac{\omega}{2} E^2 - E a_j + \frac{1}{2} m_j^2 + \frac{\theta}{2} a_j^2 \quad (2)$$

where $\theta \equiv \gamma_M \frac{\gamma_A + \gamma_E}{\gamma_E^2} > 0$ is a parameter accounting for the impact of adaptive measures on both the adaptation and environmental costs.

The optimization problem for country j is then

$$\min_{m_j, a_j} c_j = \frac{\omega}{2} E^2 - E a_j + \frac{1}{2} m_j^2 + \frac{\theta}{2} a_j^2 \quad (3)$$

with

$$E = \sum_{j=1}^n (1 - m_j) = n - m_j - \sum_{k \neq j} m_k.$$

Note that $\theta\omega = \frac{\gamma_A + \gamma_E}{\gamma_E} > 1$, which ensures that the cost function of an individual country, given the environmental strategies of the other countries, is strictly convex.

Although countries are symmetric with respect to their baseline output and cost parameters, we assume that they do not have the same attitude towards environmental problems. Indeed, we distinguish between two groups of countries. In the first group, countries agree to coordinate their environmental policies by minimizing their joint total environmental cost, and we call them *coordinating* countries. Because of the symmetry assumption, joint decisions are identical across coordinating countries. The second group is made up of countries that establish their environmental policies by minimizing their own individual overall environmental cost, and we call them *individualistic* countries. In the sequel, variables pertaining to coordinating countries are indexed by C , while those pertaining to non-coordinating countries are indexed by I . The proportion of coordinating countries is given by p , and the proportion of individualistic countries is denoted $q \equiv 1 - p$.

3 Types of adaptation

In order to address the strategic role of timing and commitment to environmental policies, we consider in this section two different assumptions about the sequence of decisions made by countries. Under the first assumption, countries commit to self-protective adaptation measures before deciding on their mitigation levels; this commitment may be taken for strategic reasons, or may be due to the fact that adaptation requires a prior investment. Under the second assumption, there is no prior commitment by countries to adaptation, which then plays no strategic role since it results in a private good.

3.1 Adaptation as a prior investment

We first analyze the situation in which adaptation requires a prior investment, and mitigation decisions are dependent on adaptation choices that have been committed to by players. This is modelled as a two-stage game solved by backward induction.

Starting from the second stage mitigation game, a representative coordinating country solves

$$\min_{m_C} c_C = \left\{ \frac{\omega}{2} (n - npm_C - M_I)^2 - (n - npm_C - M_I) a_C + \frac{1}{2} m_C^2 + \frac{\theta}{2} a_C^2 \right\}$$

where M_I denotes the total mitigation effort of non-coordinating players, and a_C denotes the joint adaptation decision of coordinating countries. From the first-order condition we derive the reaction function

$$m_C^{PNr}(M_I, a_C) = \frac{n^2 p \omega}{n^2 p^2 \omega + 1} - \frac{np \omega}{n^2 p^2 \omega + 1} M_I - \frac{np}{n^2 p^2 \omega + 1} a_C. \quad (4)$$

Start with $np + 1$ players cooperating in the adaptation game, and np in the mitigation game.

$$\begin{aligned} \frac{d}{dm} \left(\frac{\omega}{2} (n - npm - M_I)^2 - (n - npm - M_I - m_D) a_C + \frac{1}{2} m^2 + \frac{\theta}{2} a_C^2 \right) \\ m_C = - \frac{1}{n^2 p^2 \omega + 1} (np a_C - n^2 p \omega + np \omega (M_I + m_D)) \end{aligned}$$

For a representative non-coordinating country, the optimization problem to solve is given by

$$\min_{m_{Ij}} c_{Ij} = \left\{ \frac{\omega}{2} (n - m_{Ij} - npm_C - M_{I-j})^2 - (n - m_{Ij} - npm_C - M_{I-j}) a_{Ij} + \frac{1}{2} m_{Ij}^2 + \frac{\theta}{2} a_{Ij}^2 \right\}$$

where M_{I-j} denotes the total mitigation effort by the other non-coordinating countries. The corresponding reaction function is given by

$$m_{Ij}^{PNr}(m_C, A_I, a_{Ij}) = \frac{n\omega}{nq\omega + 1} - \frac{np\omega}{nq\omega + 1}m_C + \frac{\omega}{nq\omega + 1}A_I - a_{Ij}$$

For the non-coordinating countries:

$$\begin{aligned} \frac{d}{dm} \left(\frac{\omega}{2} (n - m - npm_C - (nq - 1)m_I - m_D)^2 - (n - m - npm_C - M_J - m_D)a_I + \frac{1}{2}m^2 + \frac{\theta}{2}a_I^2 \right) = \\ m + a_I + m\omega - n\omega + \omega M_J + \omega m_D + np\omega m_C = \\ m + a_I + m\omega - n\omega + \omega(nq - 2)m + \omega m_D + np\omega m_C = 0, \text{ Solution is:} \\ m_I = -\frac{1}{-\omega + nq\omega + 1} (a_I - n\omega + \omega m_D + np\omega m_C) \end{aligned}$$

For the deviating country:

$$\begin{aligned} \frac{d}{dm} \left(\frac{\omega}{2} (n - m - npm_C - M_I)^2 - (n - m - npm_C - M_I)a_I + \frac{1}{2}m^2 + \frac{\theta}{2}a_I^2 \right) = \\ m + a_I + m\omega - n\omega + \omega M_I + np\omega m_C = 0, \text{ Solution is:} \\ m_D = -\frac{1}{\omega + 1} (a_D - n\omega + \omega m_I (nq - 1) + np\omega m_C) \end{aligned}$$

Equilibrium solution:

$$\begin{aligned} m_D &= -\frac{1}{\omega + 1} (a_D - n\omega + \omega m_I (nq - 1) + np\omega m_C) \\ m_I &= -\frac{1}{-\omega + nq\omega + 1} (a_I - n\omega + \omega m_D + np\omega m_C) \\ m_C &= -\frac{1}{n^2 p^2 \omega + 1} (npa_C - n^2 p\omega + np\omega ((nq - 1)m_I + m_D)) \end{aligned}$$

where A_I denotes the total adaptation by non-cooperating countries, and a_{Ij} is the adaptation decision of non-coordinating country j . This reaction function presents the same characteristics as (4): it is negatively related to coordinating countries' mitigation and to its own adaptation. Moreover, it is positively related to the adaptation of the other non-coordinating countries, as an increase in the other countries' adaptation expenditures leads to an increase in the total pollution.

The solution of the second-stage mitigation game is the subgame-perfect Nash equilibrium given by the simultaneous solution of the reaction functions, that is:

$$m_C^{PNs}(a_C, A_I) = np \frac{n\omega - (nq\omega + 1)a_C + \omega A_I}{n^2 p^2 \omega + nq\omega + 1} \quad (5)$$

$$m_{Ij}^{PNs}(a_C, A_I, a_{Ij}) = \frac{n\omega + n^2 p^2 \omega a_C + \omega A_I}{n^2 p^2 \omega + nq\omega + 1} - a_{Ij}. \quad (6)$$

Note that the equilibrium mitigation decisions depend on the investment in adaptation measures from both types of countries, so it is interesting to understand how these decisions are affected by changes in adaptation policies. For example, if collaborating countries jointly increase their investment in adaptive measures, this allows them to decrease their mitigation effort, as they become less vulnerable to the negative impact of pollution. The same increase in adaptive measures makes the individualists' mitigation task more difficult, as an increase in emissions from coordinating countries hurts non-coordinators, which are forced to give a stronger response in terms of emissions reduction. In the same way, when a non-coordinating country unilaterally increases its adaptation investment, this leads to a decrease in the mitigation effort of that country and to an increase in the mitigation effort of all the others. This shows how both types of countries,

by choosing their adaptive measures in the first stage, can strategically affect the result of the mitigation game.⁴

The total emissions for the subgame-perfect Nash equilibrium are given by

$$E^{PNs}(a_C, A_I) = \frac{n + n^2 p^2 a_C + A_I}{n^2 p^2 \omega + nq\omega + 1}, \quad (7)$$

where it is apparent that an increase in adaptive measures against climate change leads to an increase in total emissions. Notice that total emissions are negatively related to the environmental sensitivity parameter ω .

In the first stage, players take into account the Nash equilibrium solutions (5), (6), (7), and a representative coordinating country computes its investment in adaptation by solving

$$\min_{a_C} c_C = \left\{ \frac{\omega}{2} (E^{PNs}(a_C, A_I))^2 - (E^{PNs}(a_C, A_I)) a_C + \frac{1}{2} (m_C^{PNs}(a_C, A_I))^2 + \frac{\theta}{2} a_C^2 \right\}.$$

From the first-order condition, we derive the reaction function

$$a_C^{PNr}(A_I) = \frac{(n^2 p^2 \omega + 1)(nq\omega + 1)(A_I + n)}{\theta(n^2 p^2 \omega + nq\omega + 1)^2 - n^2 p^2(n^2 p^2 \omega - n^2 q^2 \omega^2 + 1)}, \quad (8)$$

which is positively related to the adaptation effort of non-coordinating countries, meaning that preventative actions taken against the countries' impact on climate change are strategic complements.

A representative non-coordinating country chooses its adaptation level by solving

$$\min_{a_{Ij}} c_{Ij} = \left\{ \frac{\omega}{2} (E^{PNs}(a_C, A_I))^2 - (E^{PNs}(a_C, A_I)) a_{Ij} + \frac{1}{2} (m_{Ij}^{PNs}(a_C, A_I, a_{Ij}))^2 + \frac{\theta}{2} a_{Ij}^2 \right\}.$$

From the first-order conditions, we find a similar complementarity in the reaction of non-coordinating countries to the adaptation commitment of collaborating countries, that is,

$$a_I^{PNr}(a_C) = \frac{n(\omega + 1)(np^2 a_C + 1)(n^2 p^2 \omega + nq\omega + 1 - \omega)}{\theta(n^2 p^2 \omega + nq\omega + 1)^2 + \omega(n^2 p^2 \omega + 1)(n^2 p^2 + nq - 1) - nq(n^2 p^2 \omega + nq\omega + 1)}. \quad (9)$$

The solution of the system (8)-(9) gives the equilibrium solution of the whole game:

$$\begin{aligned} a_C^{PN} &= n \frac{\omega^2(Y + 1)(X + 1)(X + Y - \omega + \theta W)}{K_1} \\ a_I^{PN} &= n \frac{\omega(\omega + 1)(W - \omega)(\theta\omega W + XY)}{K_1} \\ m_C^{PN} &= n^2 p \omega^2 W(\theta\omega - 1) \frac{X + Y - \omega + \theta W}{K_1} \\ m_I^{PN} &= n\omega W(\theta\omega - 1) \frac{XY + \theta\omega W}{K_1} \end{aligned}$$

where

$$X = n^2 p^2 \omega \quad (10)$$

$$Y = nq\omega \quad (11)$$

$$W = X + Y + 1 \quad (12)$$

$$\begin{aligned} K_1 &= \theta^2 \omega^2 W^3 + \omega(X + 1)(X - W\theta\omega)(\omega - X - Y) \\ &\quad - W(XY^2 + \theta\omega((Y + 1)(X + Y) + X(X - Y^2))) \\ &> 0. \end{aligned}$$

A comparison between coordinators and individualists shows that, when adaptive measures are a prior investment with respect to mitigation levels, a collaborating country always adapts and mitigates more than a non-collaborating country, and therefore suffers a greater environmental cost ($a_C^{PN} > a_I^{PN}$, $m_C^{PN} > m_I^{PN}$, $c_C^{PN} > c_I^{PN}$).

⁴A similar strategic effect is found in Zehaie (2009).

3.2 Adaptation as a concurrent investment

We now study the case where adaptation and mitigation decisions are made concurrently by the players. This means that a representative collaborator solves

$$\min_{m_C, a_C} c_C = \left\{ \frac{\omega}{2} (n - npm_C - M_I)^2 - (n - npm_C - M_I) a_C + \frac{1}{2} m_C^2 + \frac{\theta}{2} a_C^2 \right\}$$

yielding the first-order conditions

$$\begin{cases} m_C = \frac{n^2 p \omega}{n^2 p^2 \omega + 1} - \frac{np \omega}{n^2 p^2 \omega + 1} M_I - \frac{np}{n^2 p^2 \omega + 1} a_C \\ a_C = \frac{n - npm_C - M_I}{\theta} \end{cases}.$$

Note that the optimal expenditure in adaptive measures is proportional to the total emissions.⁵

By solving the FOCs above we derive the reaction functions of collaborating countries as

$$\begin{aligned} m_C^{SNr}(M_I) &= \frac{np(\theta\omega - 1)(n - M_I)}{\theta + n^2 p^2 (\theta\omega - 1)} \\ a_C^{SNr}(M_I) &= \frac{n - M_I}{\theta + n^2 p^2 (\theta\omega - 1)} \end{aligned}$$

which clearly shows that mitigation decisions are still strategic substitutes between the two types of countries.

A representative non-coordinating country solves the optimization problem

$$\min_{m_{Ij}, a_{Ij}} c_{Ij} = \left\{ \frac{\omega}{2} (n - m_{Ij} - npm_C - M_{I-j})^2 - (n - m_{Ij} - npm_C - M_{I-j}) a_{Ij} + \frac{1}{2} m_{Ij}^2 + \frac{\theta}{2} a_{Ij}^2 \right\} \quad (13)$$

with first-order conditions

$$\begin{cases} m_I = \frac{n\omega}{nq\omega + 1} - \frac{np\omega}{nq\omega + 1} m_C - \frac{1}{nq\omega + 1} a_I \\ a_I = \frac{n - npm_C - M_I}{\theta} \end{cases}.$$

The reaction functions are then

$$\begin{aligned} m_I^{SNr}(m_C) &= \frac{n(\theta\omega - 1)(1 - pm_C)}{\theta + nq(\theta\omega - 1)} \\ a_I^{SNr}(m_C) &= \frac{n(1 - pm_C)}{\theta + nq(\theta\omega - 1)}. \end{aligned}$$

Examining the reaction functions we find that adaptation decisions no longer play any strategic role. As in the prior-commitment case, mitigation decisions by the two types of countries are strategic complements; in addition, adaptation decisions are also strategic complements to the mitigation decisions of the other players.

The solution of the whole game is then given by

$$\begin{aligned} m_C^{SN} &= \frac{n^2 p (\theta\omega - 1)}{\theta + n(q + np^2)(\theta\omega - 1)} \\ m_I^{SN} &= \frac{n(\theta\omega - 1)}{\theta + n(q + np^2)(\theta\omega - 1)} \\ a_C^{SN} &= a_I^{SN} = \frac{n}{\theta + n(q + np^2)(\theta\omega - 1)} \\ E^{SN} &= \frac{n\theta}{\theta + n(q + np^2)(\theta\omega - 1)} \\ c_C^{SN} &= \frac{n^2 (\theta\omega - 1) (\theta + n^2 p^2 (\theta\omega - 1))}{2 (\theta + n(q + np^2)(\theta\omega - 1))^2} \\ c_I^{SN} &= \frac{n^2 (\theta\omega - 1) (\theta + \theta\omega - 1)}{2 (\theta + n(q + np^2)(\theta\omega - 1))^2}. \end{aligned}$$

⁵This is similar to what was found in Ebert and Welsch (2012) for welfare maximization by one country.

A comparison between coordinating and non-coordinating countries yields that, when adaptation and mitigation are established at the same time, coordinators and individualists allocate the same amount of resources to adaptation ($a_C^{SN} = a_I^{SN}$), as adaptive expenditures are private investments proportional to total emissions. There is no strategic effect of adaptation policies between the two groups of countries. However, relative to the mitigation policy, individualistic countries take advantage of the positive externality generated by collaborators and mitigate less ($m_C^{SN} > m_I^{SN}$). This generates a lower mitigation cost and, consequently, non-collaborating countries suffer a smaller environmental cost than do collaborating countries ($c_I^{SN} < c_C^{SN}$).

4 Leadership in environmental policies

We consider again the two types of adaptive investments but we now introduce the hypothesis that coordinating countries act as leaders in both mitigation and adaptation decisions while non-coordinating countries behave as followers.

4.1 Adaptation as a prior investment

In this case we assume that countries commit to adaptation before mitigation, and that coordinating countries act as leaders, both for adaptation and mitigation decisions. We model this situation as a two-stage Stackelberg game and we solve it by backward induction starting from the second stage, where a representative non-coordinating country chooses its mitigation level by minimizing

$$\min_{m_{Ij}} c_{Ij} = \left\{ \frac{\omega}{2} (n - m_{Ij} - npm_C - M_{I-j})^2 - (n - m_{Ij} - npm_C - M_{I-j}) a_{Ij} + \frac{1}{2} m_{Ij}^2 + \frac{\theta}{2} a_{Ij}^2 \right\}.$$

As in Section 3.1, the reaction function of a representative non-coordinating country is given by

$$m_{Ij}^{PLr}(m_C, A_I, a_{Ij}) = \frac{n\omega}{nq\omega + 1} - \frac{np\omega}{nq\omega + 1} m_C + \frac{\omega}{nq\omega + 1} A_I - a_{Ij},$$

and total mitigation by non-coordinating countries is then

$$M_I^{PLr}(m_C, A_I) = \frac{n^2 q\omega - n^2 p q \omega m_C - A_I}{nq\omega + 1}.$$

A representative coordinating country, acting as a leader, anticipates the follower's reaction function and, in its second-stage mitigation game, solves

$$\min_{m_C} c_C = \left\{ \frac{\omega}{2} (n - npm_C - M_I^{PLr}(m_C, A_I))^2 - (n - npm_C - M_I^{PLr}(m_C, A_I)) a_C + \frac{1}{2} m_C^2 + \frac{\theta}{2} a_C^2 \right\}.$$

Its best response, given by

$$m_C^{PLr}(a_C, A_I) = \frac{n^2 p\omega}{n^2 p^2 \omega + (nq\omega + 1)^2} - \frac{np(nq\omega + 1)}{n^2 p^2 \omega + (nq\omega + 1)^2} a_C + \frac{np\omega}{n^2 p^2 \omega + (nq\omega + 1)^2} A_I,$$

presents similar features as the case without leadership.

The subgame-perfect Stackelberg equilibrium in mitigation is

$$\begin{aligned} m_C^{PLs}(a_C, A_I) &= \frac{n^2 p\omega}{n^2 p^2 \omega + (nq\omega + 1)^2} \\ &\quad - \frac{np(nq\omega + 1)}{n^2 p^2 \omega + (nq\omega + 1)^2} a_C + \frac{np\omega}{n^2 p^2 \omega + (nq\omega + 1)^2} A_I \\ m_{Ij}^{PLs}(a_C, A_I, a_{Ij}) &= \frac{(nq\omega + 1)n\omega}{n^2 p^2 \omega + (nq\omega + 1)^2} \\ &\quad + \frac{n^2 p^2 \omega}{n^2 p^2 \omega + (nq\omega + 1)^2} a_C + \frac{(nq\omega + 1)\omega}{n^2 p^2 \omega + (nq\omega + 1)^2} A_I - a_{Ij} \end{aligned} \tag{14}$$

and the corresponding total emissions are given by

$$E^{PLs}(a_C, A_I) = \frac{n(nq\omega + 1) + n^2p^2a_C + (nq\omega + 1)A_I}{n^2p^2\omega + (nq\omega + 1)^2}. \quad (15)$$

We observe that, as in the case without leadership, adaptation as a prior investment can be used strategically to influence mitigation policies.

Moving to the first stage of the sequential game, the equilibrium mitigation levels (14) and (15) are taken into account by each non-coordinating country, which selects its investment in adaptive measures by solving

$$\min_{a_{Ij}} c_{Ij} = \left\{ \frac{\omega}{2} (E^{PLs}(a_C, A_I))^2 - (E^{PLs}(a_C, A_I)) a_{Ij} + \frac{1}{2} (m_{Ij}^{PLs}(a_C, A_I, a_{Ij}))^2 + \frac{\theta}{2} a_{Ij}^2 \right\},$$

which gives the best response function

$$a_I^{PLr}(a_C) = \frac{(\omega + 1) \left(X + (Y + 1)^2 - \omega(Y + 1) \right) (n\omega(Y + 1) + Xa_C)}{\omega \left(\left(X + (Y + 1)^2 \right) \left(\theta \left(X + (Y + 1)^2 \right) - nq(Y + 1) \right) + (X + (Y + 1)(Y - \omega))W \right)}$$

where constants X , Y and W are defined in (10)-(12). If collaborating countries increase their expenditures on adaptive measures, non-collaborating countries react by doing the same.

We then have

$$\begin{aligned} E^{PLr}(a_C) &= \frac{(n\omega(Y + 1) + Xa_C)(U + \theta G)}{H} \\ m_C^{PLr}(a_C) &= np \left(\frac{a_C(-\omega U + G(Y - \theta\omega(Y + 1))) + n\omega^2(U + \theta G)}{H} \right) \\ m_I^{PLr}(a_C) &= \frac{H + W(\omega + 1)(\omega(Y + 1) - G)}{GH} (n\omega(Y + 1) + Xa_C) \end{aligned}$$

where

$$\begin{aligned} H &= (\theta\omega G^2 + \omega WU - YG(Y + 1)) \\ U &= (X + (Y + 1)(Y - \omega)) \\ G &= ((Y + 1)^2 + X). \end{aligned}$$

Finally, collaborating countries solve the optimization problem

$$\min_{a_C} c_C = \left\{ \frac{\omega}{2} (E^{PLr}(a_C))^2 - (E^{PLr}(a_C)) a_C + \frac{1}{2} (m_C^{PLr}(a_C))^2 + \frac{\theta}{2} a_C^2 \right\}$$

and the solution of the whole game is then

$$\begin{aligned} a_C^{PL} &= \frac{n\omega^2(U + \theta G)((Y + 1)H - XY(G + \omega U))}{K_2} \\ a_I^{PL} &= \frac{n\omega(\omega + 1)(XY(G + \omega U) - \theta\omega(Y + 1)H)(\omega(Y + 1) - G)}{K_2} \\ m_C^{PL} &= n^2p\omega^2(U + \theta G) \frac{-\omega UW + YG(Y + 1) + \theta\omega(H - G^2)}{K_2} \\ m_I^{PL} &= n\omega \frac{(H + W(\omega + 1)(\omega(Y + 1) - G))(\theta\omega H(Y + 1) - XY(G + \omega U))}{K_2 G} \end{aligned}$$

where

$$K_2 = (\theta\omega(H^2 - \theta\omega XG^3) + X(\omega^2 U^2(X + 1) + Y^2 G^2 - 2\omega U(H + YG))).$$

A comparison between leading coordinators and following individualists shows that, when adaptation is a prior investment, a collaborating leader country always adapts less than does a non-collaborating follower country, which is the opposite of what is found with prior adaptive investments and no leadership. The comparison of mitigation expenditures and overall environmental costs shows ambiguous results.

4.2 Adaptation as a concurrent investment

In this section adaptation and mitigation are decided on at the same time; however, non-coordinating countries' choices for both policies are anticipated by coordinating players. The reaction of a non-coordinating country to an announcement by the leaders is obtained by solving (13), which yields

$$\begin{aligned} m_I^{SLr}(m_C) &= \frac{n(\theta\omega - 1)(1 - pm_C)}{\theta + nq(\theta\omega - 1)} \\ a_I^{SLr}(m_C) &= \frac{n(1 - pm_C)}{\theta + nq(\theta\omega - 1)}. \end{aligned}$$

It is important to highlight that, as in the game without leadership, non-coordinators' mitigation choices are not affected by what is announced by the leaders in terms of their adaptation policy. Even when coordinating countries are leaders, adaptation has no strategic effect on non-coordinators' decisions. Adaptation expenditures are still a proportion of the total emissions. However, if leaders declare that they will increase their mitigation levels, followers will respond by reducing their effort in both environmental policies.

These reactions are anticipated by the coordinating countries, whose optimization problem is given by

$$\min_{m_C, a_C} c_C = \left\{ \frac{\omega}{2} (n - npm_C - nqm_I^{SLr}(m_C))^2 - (n - npm_C - nqm_I^{SLr}(m_C)) a_C + \frac{1}{2} m_C^2 + \frac{\theta}{2} a_C^2 \right\}$$

yielding

$$\begin{aligned} a_C^{SL} &= n \frac{\theta + nq(\theta\omega - 1)}{\theta((nq\omega + 1)(\theta(nq\omega + 1) - 2nq) + n^2p^2(\theta\omega - 1)) + n^2q^2} \\ m_C^{SL} &= \frac{\theta n^2 p (\theta\omega - 1)}{\theta^2 (n^2 p^2 \omega + (nq\omega + 1)^2) - \theta n (2q(nq\omega + 1) + np^2) + n^2 q^2}. \end{aligned}$$

The solution of the whole game is:

$$\begin{aligned} a_C^{SL} &= a_I^{SL} = n \frac{\theta + nq(\theta\omega - 1)}{\theta((nq\omega + 1)(\theta(nq\omega + 1) - 2nq) + n^2p^2(\theta\omega - 1)) + n^2q^2} \\ m_C^{SL} &= \frac{\theta n^2 p (\theta\omega - 1)}{\theta((nq\omega + 1)(\theta(nq\omega + 1) - 2nq) + n^2p^2(\theta\omega - 1)) + n^2q^2} \\ m_I^{SL} &= \frac{n(\theta - nq + \theta nq\omega)(\theta\omega - 1)}{\theta((nq\omega + 1)(\theta(nq\omega + 1) - 2nq) + n^2p^2(\theta\omega - 1)) + n^2q^2} \\ E^{SL} &= \theta n \frac{\theta + nq(\theta\omega - 1)}{\theta((nq\omega + 1)(\theta(nq\omega + 1) - 2nq) + n^2p^2(\theta\omega - 1)) + n^2q^2} \\ c_C^{SL} &= \frac{\theta n^2 (\theta\omega - 1)}{2(\theta((nq\omega + 1)(\theta(nq\omega + 1) - 2nq) + n^2p^2(\theta\omega - 1)) + n^2q^2)} \\ c_I^{SL} &= \frac{n^2(\theta\omega - 1)(\theta + \theta\omega - 1)(\theta + nq(\theta\omega - 1))^2}{2(\theta((nq\omega + 1)(\theta(nq\omega + 1) - 2nq) + n^2p^2(\theta\omega - 1)) + n^2q^2)^2}. \end{aligned}$$

A comparison between coordinating and non-coordinating countries shows that, as in the no-leadership case, both types of countries behave in the same way in terms of adaptation. For all the other variables, we derive ambiguous results.

5 Singular type cases

In this section we specialize our previous results to three singular type cases, namely: when all countries are collaborators ($p = 1$), which corresponds to the first best solution; when all countries act individually ($q = 1$) and adaptation is a prior investment; and when all countries act individually ($q = 1$) and adaptation and mitigation decisions are concurrent.

5.1 First best solution

In the first best solution, the timing of decisions does not matter, as all countries coordinate their actions, nobody is behaving strategically and all countries solve the joint optimization problem. The solution of this cooperative game is given by

$$\begin{aligned} a_{C1} &= \frac{n}{\theta + n^2 (\theta\omega - 1)} \\ m_{C1} &= n^2 \frac{\theta\omega - 1}{\theta + n^2 (\theta\omega - 1)} \\ E_{C1} &= \frac{\theta n}{\theta + n^2 (\theta\omega - 1)} \\ c_{C1} &= \frac{(\theta\omega - 1) n^2}{2 (\theta + n^2 (\theta\omega - 1))}. \end{aligned}$$

5.2 Adaptation as a prior investment without coordination

We now consider the case where no countries are collaborating ($q = 1$), and investments in adaptive measures are committed to before the mitigation decisions. This means solving a two-stage game where countries decide about their irreversible adaptation investments in the first stage and then choose their mitigation policy in the second stage. The game is solved by backward induction and the equilibrium solution is given by

$$\begin{aligned} a_{I1}^{PN} &= \frac{n (\omega + 1) (-\omega + n\omega + 1)}{\theta (n\omega + 1)^2 - n\omega (n - 1) - \omega - n} \\ m_{I1}^{PN} &= \frac{n (\theta\omega - 1) (n\omega + 1)}{\theta (n\omega + 1)^2 - n\omega (n - 1) - \omega - n} \\ E_{I1}^{PN} &= n \frac{\theta (n\omega + 1) + \omega (n - 1)}{\theta (n\omega + 1)^2 - n - \omega - n\omega (n - 1)} \\ c_{I1}^{PN} &= \frac{1}{2} n^2 (\omega + 1) (\theta\omega - 1) \frac{\theta (n\omega + 1)^2 + \omega (\omega (n - 1)^2 - 1) - 1}{(\theta (n\omega + 1)^2 - n - \omega - n\omega (n - 1))^2}. \end{aligned}$$

5.3 Adaptation as a concurrent investment without coordination

We finally consider the case where no countries are collaborating ($q = 1$) and adaptation and mitigation levels are established simultaneously. The solution of the game is given by

$$\begin{aligned} m_{I1}^{SN} &= \frac{n (\theta\omega - 1)}{\theta + n (\theta\omega - 1)} \\ a_{I1}^{SN} &= \frac{n}{\theta + n (\theta\omega - 1)} \\ E_{I1}^{SN} &= \frac{\theta n}{\theta + n (\theta\omega - 1)} \\ c_{I1}^{SN} &= \frac{n^2 (\theta\omega - 1) (\theta + \theta\omega - 1)}{2 (\theta - n + \theta n\omega)^2}. \end{aligned}$$

A comparison among the three singular type cases shows that

$$\begin{aligned} c_{I1}^{PN} &> c_{I1}^{SN} > c_{C1} \\ a_{I1}^{PN} &> a_{I1}^{SN} > a_{C1} \\ m_{I1}^{PN} &< m_{I1}^{SN} < m_{C1} \\ E_{I1}^{PN} &> E_{I1}^{SN} > E_{C1}, \end{aligned}$$

which means that, if all countries act individualistically and investments in adaptation are decided on before mitigation levels, countries suffer the highest environmental cost. This is due to the fact that, when decision about adaptation measures are made before mitigation levels are selected, countries use their investments in self-protective measures strategically, so that, by reducing their vulnerability to climate change effects, they can mitigate less. A better option in terms of environmental cost is to carry out adaptation and mitigation efforts simultaneously, which implies smaller adaptive expenditures and a greater mitigation effort.

6 Results

In this section we assess the impact of commitment and of the timing of adaptive investments for the mixed case with collaborators and individualists. The results are based both on analytical proofs and numerical investigations. We develop our evaluation by first looking at the aggregate of countries and then at each single group.

Starting from the global environmental cost, we confirm the result found for the singular type cases: in the mixed case with collaborators and individualists, committing to adaptation decisions before deciding on mitigation levels generates the highest overall environmental cost, and a better outcome is achieved when the two environmental policies are established simultaneously.

$$c_{C1} < c^{SN} < c^{PN}.$$

This is an important result, as it qualifies the AR5 statement about adaptation and mitigation as complementary strategies for reducing and managing the risks of climate change, by noting that to achieve efficient results, these strategies should be established simultaneously. The relationships found for the total environmental cost also hold for the aggregate level of adaptation and for total pollution emissions.

$$\begin{aligned} a_{C1} &< a^{SN} < a^{PN} \\ E_{C1} &< E^{SN} < E^{PN}. \end{aligned}$$

Analyzing individual performances by country in terms of environmental cost, the results obtained for the aggregate group of countries are also true for collaborating countries, that is, simultaneous decisions about adaptation and mitigation yield a greater environmental cost compared to the first best solution, while this cost is still lower than when adaptation is a prior commitment:

$$c_{C1} < c_C^{SN} < c_C^{PN}.$$

The result is slightly different for the individualist countries. Indeed, no matter how they time adaptive investments, individualistic countries can outperform the first best solution in some cases, namely when there is a relatively large number of coordinating countries. This happens because coordinators choose aggressive environmental policies that allow non-coordinating countries to free-ride and be in a better position than in the first best solution. However, it is still the case for non-collaborators that committing to adaptive investments before deciding about mitigation policies always achieves a worse result.

$$\begin{aligned} c_{C1} &\geq c_I^{SN} \\ c_{C1} &\geq c_I^{PN} \\ c_I^{SN} &< c_I^{PN}. \end{aligned}$$

Moving to the individual equilibrium decisions, and starting with the adaptation levels, the results found in the aggregate case are confirmed for both individualists and collaborators, all of which assign too many resources to adaptive measures with respect to the first best solution, more so when adaptation requires a prior investment:

$$\begin{aligned} a_{C1} &< a_C^{SN} < a_C^{PN} \\ a_{C1} &< a_I^{SN} < a_I^{PN}. \end{aligned}$$

Continuing with mitigation decisions, we find that, in some cases, collaborators may curtail their emissions more than in the first best solution, for both types of adaptive investment. This occurs when the mitigation cost coefficient γ_M is large compared to the environmental sensitivity γ_I . In other words, coordinating countries mitigate more than in the first best solution when mitigation is relatively expensive. This is an interesting result since collaborators always adapt more than in the first best solution; the coexistence with individualistic countries may push collaborating countries to inefficiently high levels of emission reductions, even with a higher adaptation investment.

$$\begin{aligned} m_{C1} &\geq m_C^{SN} \\ m_{C1} &\geq m_C^{PN}. \end{aligned}$$

On the other hand, non-collaborators always mitigate less than under the first best solution, regardless of the timing of adaptive investments:

$$\begin{aligned} m_{C1} &> m_I^{SN} \\ m_{C1} &> m_I^{PN}. \end{aligned}$$

We now compare the mitigation level under the two assumptions about the nature of adaptation. Collaborating countries always mitigate less when adaptation investments are selected before the mitigation levels, compared to when both policies are established at the same time. This is due to a strategic effect: when adaptation is timed before mitigation, countries adapt more, they become less vulnerable to the effects of climate change and, as a consequence, they mitigate less:

$$m_C^{SN} > m_C^{PN}.$$

However, this strategic effect is not always confirmed for non-collaborating countries. Indeed, pre-committing to some adaptive measures brings a larger mitigation effort from non-collaborating countries if the two following conditions are satisfied:

$$\begin{aligned} \omega &> \frac{n^2 p^2 + nq - 1}{n^2 p^2 (np - 1)(np + 1)(nq - 1)} \\ \theta &> \frac{n^2 p^2 ((np - 1)(np + 1)(n^2 p^2 \omega + 1)(nq - 1) + n^4 p^2 q^2 \omega)}{(n^2 p^2 \omega + nq \omega + 1)(n^2 p^2 \omega (np - 1)(np + 1)(nq - 1) + 1 - n^2 p^2 - nq)}. \end{aligned}$$

Finally, we also find that some level of collaboration is always beneficial, no matter the type of adaptive investment. That is, the global environmental cost c , the aggregate level of adaptation a and the total pollution emissions E are always less in the mixed case than when there are only individualists. In addition, non-collaborating countries suffer a lower individual environmental cost, invest fewer resources in adaptation and mitigate less when the two types of countries coexist than when they all act individually.

When we repeat the same type of analysis under the assumption that collaborating countries become leaders in responding to climate change and individualistic countries act as followers, many of the previously found results become ambiguous. However, we find at the aggregate level, under the leadership assumption, that timing adaptation decisions simultaneously with the mitigation ones causes a greater overall aggregate environmental cost compared to the first best solution, but this cost is still lower than when adaptation investments are decided on before the mitigation levels.

$$c_{C1} < c^{SL} < c^{PL}.$$

From the above we can again conclude that simultaneous investments in adaptation and mitigation give rise to more efficient policies than do prior commitments in adaptation.

In our last set of results we compare the equilibrium solutions with and without leadership, in the case where adaptation and mitigation decisions are taken simultaneously. Our findings can be summarized as follows:

$$\begin{aligned}
m_C^{SN} &> m_C^{SL} & m_I^{SN} &< m_I^{SL} \\
E^{SN} &< E^{SL} \\
a_C^{SN} &< a_C^{SL} & a_I^{SN} &< a_I^{SL} \\
c_C^{SN} &> c_C^{SL} & c_I^{SN} &< c_I^{SL} \\
c^{SN} &< c^{SL}.
\end{aligned}$$

For this type of adaptation, we find that coordinating countries, by becoming first movers and anticipating the followers' reaction, mitigate less and push the followers to mitigate more than in a game without leadership. This yields a higher total pollution and greater expenditures in adaptation for both types of countries, since adaptation is a proportion of the total pollution. In terms of individual performance, leaders are better off, suffering a lower overall environmental cost, and followers are worse off. At the aggregate level, the overall environmental cost is greater with leadership than without leadership. This is an important result because it suggests that leadership is not globally efficient; however, it would be convenient to a group of collaborating countries (e.g. Annex I Parties) to make the first move.

7 Conclusions

In this paper we developed a model where countries minimize their environmental cost by adopting two environmental policies, namely, mitigation and adaptation, with the objective of understanding the implications of different decision sequences for these policies.

One of the main results of our analysis is that the highest environmental cost suffered by countries always occurs when investments in adaptation are committed to before any decisions about mitigation levels are made (this is true in the singular type cases, in the mixed case at the aggregate level and at the individual level for both individualistic and collaborating countries, with and without leadership). As a consequence, simultaneous investments in adaptive and mitigating measures seem to be the best way to answer the problem of the effects of climate change. This is an important result because it reinforces the message stated in the AR5, while adding that the complementary environmental policies should be carried out at the same time, with a unified approach.

Another important observation is that when adaptation requires an investment prior to any mitigation arrangement, adaptation can be used strategically, that is, countries can allocate greater resources to adaptation and self-protection so that they can save on mitigation efforts, compared to the case where decisions are made simultaneously.

Finally, we showed that with simultaneous investments in adaptive and mitigating measures, having some countries taking leadership in responding to the effects of climate change is not beneficial at an aggregate level. This contrasts with what has been done for the promotion of international environmental agreements, with the distinction between Annex I and No-Annex I countries. However, from an individual point of view, countries that become leaders are able to lower their overall cost, so that it is in the interest of collaborating countries to take a first step in countering the effects of climate change.

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